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THE PETROGRAPHICAL PROVINCE OF ESSEX CO., MASS. GENERAL DISCUSSION AND CONCLUSIONS. V.

Analytical methods.—As far as was possible with the means at my disposal the methods advocated by Hillebrand[1] were followed, some slight modifications being necessary owing to lack of certain facilities in my laboratory. A word must be said in recognition of the high character of the work of the chemists of the U. S. Geological Survey. Petrologists generally are deeply indebted to them for the service they have rendered the science, not only by the investigation of methods and the very large amount of excellent work which they have done, but also for the high standard of excellence which they have set for other analysts to follow.

Ignition H_2O was determined in dry CO_2. It will be seen from the generally low summation of the rocks high in FeO that this did not entirely prevent oxidation under the conditions obtaining, but the error will not be high. The precipitation with ammonia was always made twice, and three times in the case of the basic rocks, in the presence of sufficient NH_4Cl. This is of the utmost importance, as pointed out by Pirsson[2] and Hillebrand,[3] on account of the tendency of MgO to be coprecipitated with the Al and Fe hydrates. Neglect of these precautions has rendered useless many analyses, but it is a point which is often overlooked. With one exception, MnO was not determined, since its amount was apparently small and its determination would have extended considerably the time necessary for an analysis, and hence lessened their number. Alkalis were, of course, determined by the Lawrence Smith method.

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[1] CLARKE and HILLEBRAND. Analyses of Rocks. Bull. U. S. Geol. Surv., 1897.

[2] PIRSSON, JOUR. GEOL., Vol. IV, 688, 1896.

[3] HILLEBRAND, *op. cit*, p. 39.

It must be noted that throughout this paper the terms acid and basic refer only to the relative amount of SiO_2, no connotation of the amounts of the other oxides being implied.

Use of the term petrographical province.—The idea which underlies the general use of this term is that of a region of igneous rocks which possess in common certain characters, structural, mineralogical, or chemical, and in which the characters may vary continuously from one end to the other of the series of rocks represented. The term is usually applied to large areas embracing several centers of igneous activity, which, by their similarity in character, may be presumed to be related. Its application in the title of this paper is somewhat restricted, and therefore open to criticism, but seems justified on the grounds of convenience, the evident relationship of the rocks, and the fact that this region may serve as the type of the still larger New England one.

Chemical characters.—In Table I are given my analyses of the rocks of Essex county, with one by Dr. Eakle, and in Table II the molecular amounts of the various oxides. It is to be borne in mind that all references to the relative amounts of the oxides are to their molecular amounts, and not to their percentages as obtained in the analyses.

The range in composition is very great, the rocks varying from basic gabbro with 44 to acid granite with 78 per cent. of SiO_2. Al_2O_3 varies considerably and is notably higher toward the basic end. The total amounts of iron oxides are rather high, Fe_2O_3 being low and varying little, while FeO is higher, especially so in the basic rocks. MgO and CaO behave alike, being low in the more acid rocks, and suddenly much higher in the basic. The alkalies are abundant, Na_2O more so than K_2O, but, on the whole, do not vary as much as the other constituents.

The rocks as a whole are rather acid, *i. e.*, they contain more SiO_2 than most similar types elsewhere. The granite is decidedly an acid one, the foyaites more acid than most nepheline-syenites, and the same is true of the pulaskites, the akerite and nordmarkite, the tinguaite, sölvsbergite, and paisanite. In the basic rocks, on the other hand, the opposite seems to hold good, that they are more basic than usual.

In the next place they are rich in both alkalis, and Na_2O is constantly greater than K_2O. On the whole, however, Na_2O does not predominate to such an extent as to stamp the region as essentially one of soda rocks, but is sufficiently predominant to determine the character of the types, as shown in the mineralogical composition.

In general the rocks are rich in iron oxides, FeO being especially, and in some cases abnormally, high. It may be mentioned that TiO_2 is high, comparatively speaking, and that BaO seems to be absent.

The province as a whole then, may be characterized as one of rocks which are more acid or more basic than normal, high in alkalis, with Na_2O predominating over K_2O, high in iron oxides, especially FeO, rather high in Al_2O_3, and low in MgO and CaO.

Mineralogical characters.—We find the main chemical features well expressed in the general mineralogical composition. Corresponding to the high SiO_2 and alkalis, the prevailing feldspars are albite and orthoclase, with quartz-syenites abundant. The albite molecule is very abundant, giving rise to the characteristic microperthites and the albitic syenites of the litchfieldite and pulaskite types. At the same time the soda-hornblendes and soda-pyroxenes are common. The low CaO forbids the formation of much lime-soda feldspar, which we find to be rare, and even in some of the basic rocks the plagioclase is more albitic than usual.

The paucity in MgO is of great influence. Olivine is rare even in the basic rocks. A striking peculiarity in this connection is the replacement of the deficient MgO by FeO. This gives rise to the presence of varieties of minerals normally magnesian, but which are here largely ferrous instead. This is exemplified by the abundance of the MgO-free biotites, lepidomelane and cryophyllite, as well as the occurrence of the purely ferrous olivine, fayalite[1] in the granite, and the presence of the MgO-free "glaucophane" molecule in the blue hornblendes[2] of the region.

Discussion of oxide ratios.—In Table II are given, below the molecular amounts, several oxide ratios, which we may next examine, since they serve to differentiate the rocks of the region into groups.

$\frac{Na_2O}{K_2O}$. This ratio is constantly greater than unity, as we have seen, though often closely approaching it. A striking feature is that in ten or eleven cases it is either exactly or very near a whole number; 1 : 1, 2 : 1, 3 : 1, or 6 : 1. In ten others it closely approximates to multiples of a half; 1 ½ : 1, 2 ½ : 1, 3 ½ : 1, or 6 ½ : 1. In only three or four cases does it differ more than about .12 from such figures. There seems to be a tendency for Na_2O and K_2O to exist in stoichiometric ratios with respect to each other. The same is true elsewhere, notably in the Christiania region, where Brögger[3] connects it with the tendency of the alkalis to such ratios in nepheline and soda-orthoclase. Such ratios, however, in igneous rocks are by no means general.

When we examine this ratio in the various rocks we see that it is characteristic of certain rock groups. In the granite, the quartz-syenite-porphyry and the quartz-syenites it is quite constant, varying only from 1.09 to 1.17. In the aplite dike it is a little higher, about 1.5. In the keratophyre and rhyolite it is still higher, 1.40 and 2.20. As we go toward the basic end the ratio increases, being 1.7 and 2.1 in the pulaskites, 2.2, 2.5, and 3.6 in the sölvsbergites and biotite-tinguaite, and 3.0 in the foyaites. In the basic rocks, from diorite down, the ratios are constantly high, varying from 2.6 to 6.6, and is also high, 6, in the analcite-tinguaite.

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[1] PENFIELD and FORBES: Am. Jour. Sci. (IV), I, 129, 1896.

[2] H. S. WASHINGTON: Am. Jour. Sci. (IV), VI, 179, 1898.

[3] BRÖGGER: Eruptivgesteine der Kristianiagebietes. I, 165, 1894, and III, 249, 1897.

It will be seen that in what are obviously connected series of rocks there is a regular variation in one direction, an increase toward the basic end. The most striking instance is the paisanite-tinguaite series, in which the ratios are 1.23, 2.17, 2.47, 3.62, and 5.97. Also in the pulaskite-foyaite-essexite series, where the ratios are 1.71, 2.09, 3.00, 2.98, and 3.64. The granite, quartz-syenites, diorites, and gabbros show the relation less well, though even here the ratio is markedly higher in the basic members.

These observations leave no doubt of the fact that in Essex county Na_2O increases relatively to K_2O as SiO_2 decreases. This agrees with the Christiania region, where Brögger[1] shows that in the grorudite-tinguaite series the same holds good. In both cases the effect is due chiefly to increase in Na_2O relatively to SiO_2, K_2O remaining comparatively stationary. The line giving the ratio of $Na_2O : SiO_2$ will show this for Essex county. Such a variation is not universal, as in other regions exactly the contrary obtains,[2] the K_2O increasing as SiO_2 decreases.

It is evident, therefore, that Na_2O and K_2O differentiate with respect to each other, a fact to which Pirsson has already called attention.[3] This is of theoretical interest since it indicates that, notwithstanding their general similarity, there is a difference between the two alkalis in their functions in igneous rocks, a subject which space does not permit of being treated here.

$\frac{FeO}{Fe_2O_3}$. The variations in this ratio are far greater than in the preceding, ranging from 0.37 to 16.0, but examination reveals certain regularities. It is very high in the granite, aplite, quartz-syenite, and porphyry, and in all the basic rocks. It will also be observed that it is higher in the dike rocks than in their corresponding plutonic forms. It is lower in the paisanite and sölvsbergites, still lower in the pulaskites and foyaites, as well as in the rhyolite and keratophyre, and lowest of all in the tinguaites.

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[1] BRÖGGER: *op. cit.*, Vol. III, p. 249, note 1, 1897.

[2] PIRSSON: Bull. 139 U. S. Geol. Surv., p. 138, note 5, 1896. HARKER: Geol. Mag., Vol. IX, 203, 1892.

[3] PIRSSON: Bull. 139 U. S. Geol. Surv., p. 138, 1896.

It is evident, granting that these relations are not fortuitous, which the number of analyses seems to preclude, that this ratio does not vary with the SiO_2, but seems to be dependent here on the general character of the magma from which the rocks solidified. Grouping these roughly into two classes according to their general characters we may say that the ratio is high in the granito-dioritic group and low in the foyaitic.

It is, it must be confessed, somewhat surprising to find such a connection between the ratio of the two iron oxides and the petrographical character of the rocks. Is it indeed the fact that there is such a difference in behavior between the two oxides? Do they really differentiate with respect to each other, or is the relation only apparent and due to other causes, such as possible oxidation of the ferrous iron in the foyaitic rocks? In the flow rocks the ratio is low and it seems possible that their solidification at the surface may have induced oxidation. But all the other rocks are abyssal or hypabyssal, so that such an action would seem to be excluded, or at least equally effective in each. We have also seen that the granito-dioritic dikes show a uniformly higher ratio than their plutonic analogues. On the whole we seem driven, as far as the data at hand allow us to decide, to the conclusion that the two oxides differentiate with respect to each other and that their ratio is in some way connected with the composition of the magma.

In connection with this ratio we may note the interesting case of Nos. XV and XIV, the tinguaite and sölvsbergite, whose composition is very similar, the total iron oxides being about the same. In the tinguaite the high Fe_2O_3 (ratio 0.52) has conditioned the formation of aegirite, while in the sölvsbergite the high FeO (ratio 3.31) has conditioned the formation of glaucophane-riebeckite as the colored mineral.

$\frac{Na_2O+K_2O}{SiO_2}$ This ratio has been recently employed by Iddings[1] in the investigation of the relationships of rocks. Here it corresponds in a general way with the grouping already used. In the acid rocks, from granite to akerite, the ratio is low and fairly constant, varying only from .088 to .121. In the foyaitic rocks from glaucophane-sölvsbergite to analcite-tinguaite, it is much higher and also fairly constant, from .156 to .228. In the basic rocks the ratio is again low, the essexite alone showing the high ratio of .166, analogous to that of the foyaites, as was to be expected. The ratio of the hornblende-gabbro (.112) is also in accord with its transitional character between the diorites and essexite.

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[1] IDDINGS: JOUR. GEOL., Vol. III, 956, 1895, Vol. VI, 96, 189, Vol. VI, 219, 1898.

A large number of other ratios have been examined, but without any very significant results. The only one worth mention is that of $Al_2O_3+Fe_2O_3:CaO+Na_2O+K_2O$. In the more acid rocks, from pulaskite up, this approximates closely to unity, but below this there are some other wide variations, the sesquioxides being deficient, except in the foyaites.

The rock series.—Without going further into details, we may divide the rocks of Essex county into the following series as defined by Brögger.[1]

The first may be called the *granito-dioritic*, and embraces the granites, quartz-syenites, quartz-diorites, diorites (which are partly monzonitic), and gabbro. These are characterized mineralogically by the presence of microperthite (albite and orthoclase) in the more acid members and plagioclase with some alkali-feldspar in the basic, and by iron-micas (in the more acid) and green and brown hornblendes and pyroxenes. Chemically they show comparatively low ratios of Na_2O to K_2O and Na_2O+K_2O to SiO_2, and high ratios of FeO to Fe_2O_3.

To this is related a series of dike rocks, including the aplites and microgranites, quartz-syenite-porphyry, and, at the basic end, probably a part of the diabases. These dike rocks possess chemical and mineralogical characters similar to those of the preceding series.

The next prominent series is the *foyaitic*, embracing the pulaskite, litchfieldite, and essexite, and characterized by the abundance of the albite molecule, lack of lime-soda feldspars, and presence of nepheline, aegirite, and blue glaucophane-riebeckite or brown barkevikite. These rocks show high $Na_2O:K_2O$: and $Na_2O+K_2O:SiO_2$ ratios and low $FeO:Fe_2O_3$.

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[1] BRÖGGER: Eruptivgest. d. Kristianiageb. Vol. I, p. 169, 1894.

Related to this series are the dikes of the sölvsbergite-tinguaite series, and of paisanite, also possibly the camptonitic dikes. These show chemical and mineralogical characters analogous to those of the foyaitic series, but vary far more in composition.

These four series, which are very well defined, include nearly all the rocks examined. Among the exceptions the hornblende-gabbro occupies, as we have seen, a position intermediate between the diorites and essexites, and may be reasonably regarded as a transitional and connecting form. The flow rocks are abnormal. In certain respects they seem to be allied with the granito-dioritic rocks, while other characters suggest affinities with the foyaites. The question is a difficult one to decide. The orbicular syenites, which are present in very small amount, are almost certainly related to the granito-dioritic series, though lack of an analysis leaves the question uncertain. By its mineralogical characters and by its ratios the Quincy granite belongs to a foyaitic series, forming the most acid member of it, and corresponding to the paisanites among the dike rocks. As it belongs to the Blue Hills Complex, quite outside our region, it will not be discussed further.

Relations of the various types.—As a preliminary to the determination of the genetic connection of the various rocks, it will be well to obtain some idea of the relative amounts of the different types represented. For obvious reasons it is, of course, not possible to do this with certainty or accuracy. If we assume that the areas shown on the geological map are dependent on the relative volumes (which may or may not be the case) we shall get an estimate, which, though very far from being accurate or wholly satisfactory, may be considered provisionally to express the relation in a general way, and which will probably be sufficient for our present purpose.

An examination of Mr. Sears' map, together with a consideration of my own observations, permits me to estimate, *in a very rough way*, the relative percentage areas given in the following table, in which are also given the relative volumes, reduced to percentages, calculated from these data. This estimate, it must be observed, includes only the main area of igneous rocks, excluding the area of sedimentaries and gneisses, etc., which covers the western part of the county, as well as the quartz-diorite area near Newburyport, since the northerly extension and connections of this are unknown to me.

Rock	Area, %	Volume, %
Granite	30	37.2
Quartz-syenites	24	26.4
Diorites	28	33.4
Foyaites	2	0.6
Essexite	1	0.2
Gabbro	1	0.2
Acid Dikes	1	0.2
Basic Dikes[1]	3	1.2
Rhyolite[2]	10	0.6

It will be seen that the granites and quartz-syenites constitute nearly two thirds of the total, the diorites[3] one third, while all the others make up only three per cent. This result is of special interest since this region is generally regarded by petrographers as essentially one of nepheline-syenites. They occur, it is true, but form only a small, though important, part of the complex.

[1] Shaler (*op. cit.*, p. 583) estimates the area of the dikes of Cape Ann at 5 to 10 per cent. As dikes are apparently less abundant elsewhere I have reduced this considerably, especially as my observations lead me to think it too high.

[2] As these are flow rocks their depth will be small compared to their area, and I have therefore estimated their volume at only a tenth of that calculated on the basis of the other rocks.

[3] I have recently received from Mr. Sears a large and representative collection of the diorites of the main western Ipswich-Danvers area. Although time is lacking for proper microscopical and chemical study, they are evidently quite basic, and to all appearance approximate very closely to those already described, chemically and mineralogically.

Assuming that the figures given in the table above are roughly true (which is quite hypothetical), it will be of interest to calculate the composition of the magma as a whole. The results of this calculation, which are admittedly crude and of little reliability on account of the character of the data employed, are as follows:

SiO_2,	TiO_2,	Al_2O_3,	Fe_2O_3,	FeO,	MgO,	CaO,	Na_2O,	K_2O,	H_2O, etc.
65.3	1.0	14.5	1.2	4.6	1.7	3.6	3.7	4.0	0.4=100.

The result corresponds in general with the idea of the magma derived from examination of the analyses, though it is perhaps somewhat higher in MgO and CaO, and hence more monzonitic, than we might have expected. Of the rocks analyzed it approaches most closely to that of the akerite (No. X), but it shows less SiO_2 and alkalies, and more MgO and CaO than this. A rock of this composition would probably be found among the more basic akerites or more acid diorites.

Leaving this aside for the present it will be evident that the main course of differentiation (assuming that such has taken place), has been to form a large series of granites, quartz-syenites, and diorites, which pass into one another more or less gradually through transition forms. Among these there is a quite gradual gradation of the oxides, as will be seen on reference to the table of analyses. A rather peculiar feature is the increase of Al_2O_3 in the basic members, which is quite unusual. Parallel series from other regions analogous to this might be mentioned, but it seems scarcely worth while to do so.

The series of granito-dioritic dikes, which correspond so closely both mineralogically and chemically to the granolites, must be classed as aschistic[1], *i. e.*, which are not separate differentiation forms of their magmas, but only dike forms of the partial magmas which solidified elsewhere as granolites.

The foyaitic series presents a somewhat different problem. These rocks are evidently connected genetically with the main series, both on geological grounds and petrographical, such as the transition forms between the essexite and diorites. They represent, however, a distinctly different magma; one not only more basic, but richer in Na_2O and Al_2O_3 and poorer in CaO, MgO, and FeO. They are also notable for the fact that considering their very small amount they are relatively more differentiated than the main magma. This is in accordance with observations on nepheline-syenite regions elsewhere, which, it is well known, carry not only a very great number and variety of rare component minerals, but also show a comparatively large number of rock varieties.

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[1] BRÖGGER: *op. cit.*, Vol. I, p. 125. I am in some uncertainty in thus rendering into English BRÖGGER'S words *aschist* and *diaschist*. The termination -ic would seem to be better than -ous or -ose, which latter is already in use in schistose, denoting structure.

Since it has been shown that in the granito-dioritic series Na_2O tends to increase relatively to K_2O as SiO_2 decreases, and at the same time as it increases inversely as SiO_2, it follows that in the course of a differentiation of such a magma there should be an enrichment of Na_2O at the basic end. The rocks of the foyaitic series may then be held to represent the further differentiation products of such a basic, soda-rich portion of the main magma, this further differentiation taking place in accordance with the tendency of magmas rich in soda to differentiate, while in the more acid portions the relations would remain more simple. This explanation is essentially that of Pirsson[1] to account for the phonolitic dikes of the Judith Mountains.

Lack of space forbids the full discussion of the foyaitic dike rocks, comparing them with the main types as Brögger has done, but the evidence goes to show that the paisanite, sölvsbergites, and tinguaites are probably to be regarded as diaschistic dikes, i. e., further differentiation products of the foyaitic magma, and not simply dike forms of this. This is analogous to the Christiania region, where Brögger[2] has shown that the dikes of the grorudite-tinguaite series are diaschistic.

The differentiation probably laccolithic.—We have now to examine the question as to where the differentiation of the Essex county magma took place. Are the rocks, as we see them, due to successive injections of liquid magmas and the differentiates[1] of a more deeply seated magma, only part of which was released from the reservoir, or are they the differentiates *in situ* of a body of magma which was injected in a more or less homogeneous condition from below? Is the differentiation, in other words, "deep magmatic," or "laccolithic?"[2] Very thorough and careful field study is necessary to decide this question, study which it has not been possible for me to undertake. At the same time, certain considerations seem to point to the conclusion that the differentiation at Essex county was laccolithic, and that the complex may possibly be regarded as a laccolith. I can only point out very briefly the facts on which this conclusion rests, leaving the further study and settlement of the question to others.

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[1] PIRSSON: Eighteenth Ann. Rep. U. S. Geol. Surv., p. 573, 1898.

[2] BRÖGGER: *op. cit.*, p. 127 ff.

Comparatively very few differentiated laccolithic masses have been studied, but those which we know best show a basic border and more acid interior, with, in some cases, an intermediate zone of medium composition. Prominent examples of these are Brandberget, in Gran;[3] Carrock Fell[4] in England, and the especially beautiful and instructive ones described by Weed and Pirsson, notably, Square Butte,[5] Yogo Peak,[6] and Bear Paw Peak[7] in Montana.

On looking at the geological map of Essex county,[8] it is seen that the main granite area is to the east, extending in large patches from Cape Ann westward, and ending in this

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[1] I use this term as synonymous with and more convenient than "differentiation product." It is formed analogously to the word *solute.*

[2] BROGGER: Quart. Jour. Geol. Soc., Vol. L, p. 29 ff., 1894, and Erupt. gest. d. Christ. geb., Vol I, p. 153, 1894.

[3] BROGGER: Quart. Jour. Geol. Soc., Vol. L, p. 31, 1894.

[4] HARKER: Quart. Jour. Geol. Soc., Vol. L, p. 311, 1894, and Vol. LI, p. 125, 1895.

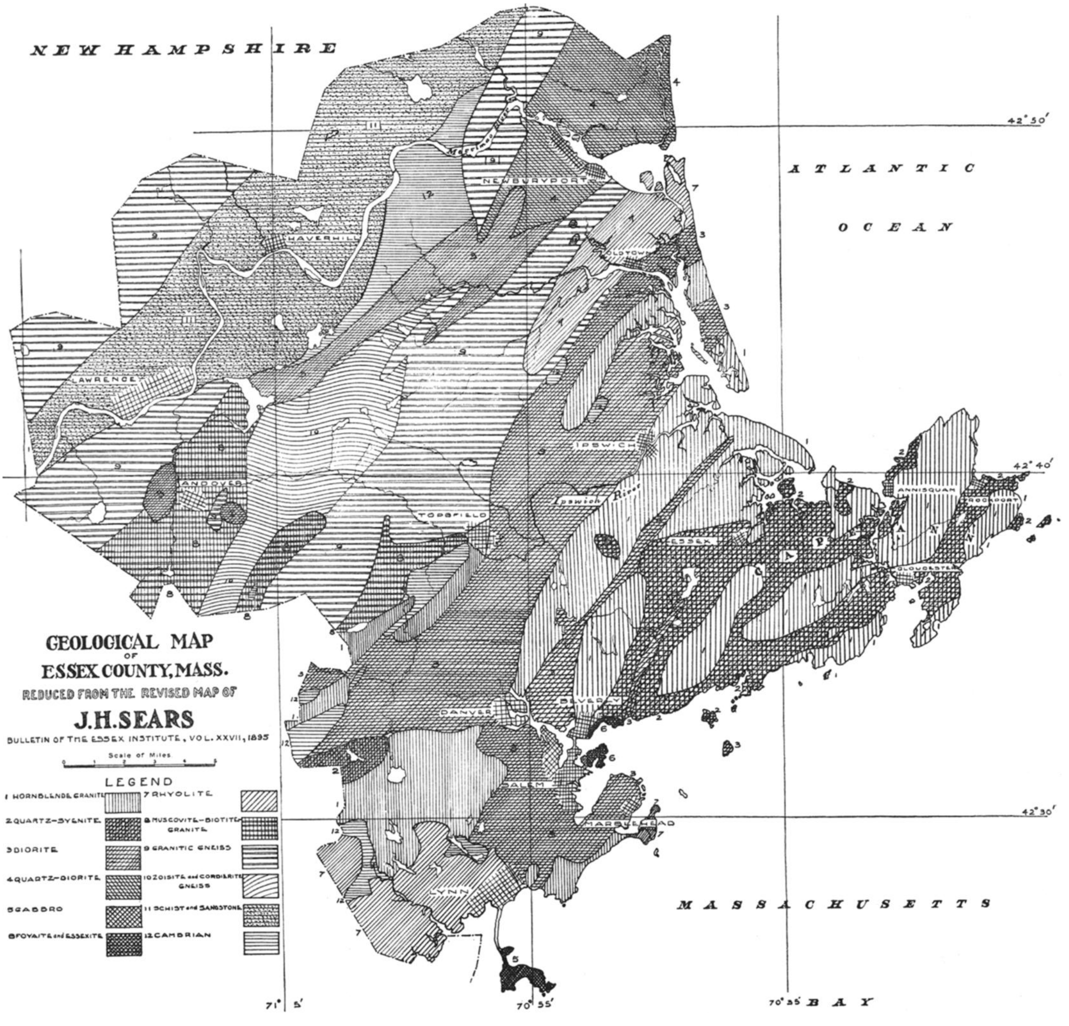
[5] WEED and PIRSSON: Bull. Geol. Soc. Am., Vol. VI, p. 389, 1895.

[6] WEED and PIRSSON: Am. Jour. Sci. Vol. L, p. 467, 1895.

[7] WEED and PIRSSON: Amer. Jour. Sci., Vol. I, p. 351, 1896.

[8] The map here given is copied from the revised one of Mr. Sears, some omissions being made on account of the greatly reduced scale. An attempt has been made to show approximately the small foyaite area along the Beverly Shore.

Jour. Geol., Vol. VII, No. 5 Plate VI



direction in a broad zone which runs north-northeast from Beverly to Ipswich. Interspersed with the granite and surrounding some of the smaller areas is quartz-syenite, which is not met with west of the granitic zone, except in two small patches. West of the granite area, and forming also a broad zone running north-northeast, is the main area of diorite, which curves around to the south, forming the Salem area, and is also met with as strips and tongues in the granite areas. West and northwest of the diorite are found sedimentary and metamorphic rocks, of which something will be said later. The small area of foyaitic rocks lies near Salem, south of the western parts of the granite and quartz-syenite areas. The gabbro is only met with at the extreme south, on the small promontory of Nahant with patches of metamorphosed Cambrian sedimentaries. To the south near Lynn, and north near Newburyport, are areas of rhyolite, a small patch of which is also found at Marblehead Neck, southeast of Salem.

There is then a rather regular arrangement, the acid rocks being to the east and the basic diorites surrounding them to west and south, lying on the outside next to the nonigneous rocks. This is suggestive of the arrangement of the rocks in the ordinary type of differentiated laccolith.

In the next place, according to Mr. Sears' map and his description of the sedimentary rocks,[1] we find that the dips of the sedimentaries and metamorphosed rocks, which form the western part of the county, are in general to the northwest or north-northwest, *i. e.*, away from the igneous area. This is also suggestive of a laccolithic mass, and the few small areas of sedimentaries metamorphosed by contact with the igneous rock, which are met with here and there through the igneous areas, may be considered to be remnants of the original cover. In fact, Mr. Sears, himself, indicates the conclusion that the mass is an anticlinal laccolith, when he says:[2] "The position of these two metamorphosed crystalline sedimentary beds signifies that they are remnants of an anticlinal fold of the Cambrian sediments, perhaps produced by the intrusion of the eruptive granite magma from beneath them."[1]

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[1] SEARS: Bull. Essex Inst., Vol. XXII, p. 1, 1890.

[2] SEARS: Bull. Essex Inst., Vol. XXIII, p. 15, 1891.

A further fact, which is in favor of laccolithic differentiation, is the radical difference of opinion of the two observers, Wadsworth and Sears, who are best acquainted with the region, as to the order of succession of the igneous rocks. Leaving the dikes out of consideration, and adopting the nomenclature of this paper, Wadsworth[2] gives it as follows, beginning with the earliest: gabbro and diorite, quartz-syenite, nepheline-syenite, granite, and rhyolite. Sears,[3] on the other hand, gives granite, quartz-diorite, essexite, diorite, nepheline-syenite, and quartz-syenite, gabbro, rhyolite. This argument is not conclusive, since the differences of opinion are perhaps explicable on the ground of lack of good exposures, etc., but in the case of two good observers, who made a careful study of the region, they are suggestive of the fact that there is no "order of succession" in the usual sense of the term, and which we would not expect to find in the case of a differentiating laccolithic mass of magma.

Lastly, it may be mentioned that the rocks are just what we might expect to find as the differentiates of a magma, such as this was, when laccolithically differentiated. The transition types which exist between the various members, and the "schlieren," such as those in the diorite of Marblehead, are also in favor of this hypothesis, as is also the greater abundance of dikes in the granites as compared with the diorites, since it seems reasonable to suppose that many cracks formed from below would penetrate the granite, and not the overlying diorite zone.

Several objections may readily be brought against this hypothesis, among which may be mentioned, the asymmetric character of the complex and the absence of quartz-syenite between the granite and diorite, where we should expect to find it. The first objection may be met with the fact that such asymmetric laccoliths are known, and are to be looked for in certain conditions of the surrounding strata.[1] Further, the presence of the coastal fault line and the Atlantic Ocean to the east is a sufficient explanation for the disappearance of a large part of the mass on this side.[2] The irregularity of the quartz-syenite is a more serious objection, and is, perhaps, best explained by the admitted fact that the laccolith must have been of a decidedly irregular shape, owing to the conformation of the strata into which it was intruded. It is possible, also, that considerable faulting may have taken place. The microscope shows that most of the rocks have been subjected to pressure, such as would be consequent on crustal movements. It must be noted that I am here using the term laccolith in a broad sense, as Cross and Pirsson have done to include "all thick lenticular (in this case elongated) masses which have domed up the strata, and have over the greater part of their area a roof of sediments"[3] (here largely disappeared through erosion, glacial, and otherwise). The actual presence of this last feature is not essential to the idea, since any cover may be removed by erosion without affecting the original character of the mass.

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[1] A similar structure is apparently suggested by HOBBS (Amer. Geol., Vol. XXII, p. 110, 1899) for the area about Waltham, southwest of our region.

[2] WADSWORTH: Geol. Mag., p. 209, 1885.

[3] SEARS: Bull. Essex Inst., Vol. XXVII, p. 109, 1895.

It may also be remarked that, as far as can be seen, the course of differentiation would be the same whether, as in a true laccolith, the intruded magma bulged up the overlying strata, or entered an arch space formed otherwise.[4] From the petrological standpoint the mechanics of the process are of secondary importance. The chief point of my suggestion is that the differentiation was laccolithic and of a mass *in situ*, and not deep magmatic, and the rocks the results of successive intrusions. In the one case the rocks are all genetically connected, in the other possibly not.

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[1] W. CROSS: Fourteenth Ann. Rep. U. S. G. S., p. 236 ff, 1895. PIRSSON: Eighteenth Ann. Rep. U. S. G. S., pp. 555, 581, 1898.

[2] MR. SEARS (Bull. Essex Inst., Vol. XXII, p. 16, 1890) notes the occurrence of Cambrian limestone at Jeffrey's Ledge, in the Atlantic Ocean, about twenty miles east of Cape Ann.

[3] PIRSSON: *loc. cit.*, p. 581.

[4] For an example of the latter cf. WATTS: Rep. Brit. Assoc. 1886, p. 670 and Proc. Geol. Assoc., 1894, p. 341.

Conclusion and summary.— My view, then, of the structure of the complex and genetic relationships of the rocks of Essex county is as follows. The igneous area represents possibly a section through an elongated, irregular, anticlinal, laccolithic mass, with a N. N. E.— S. S. W. trend, intruded into already disturbed Cambrian strata. The plutonic igneous rocks represent the products of a laccolithic differentiation in this magma, and not successive intrusions. The magma was rather acid, rich in alkalies and ferrous iron, and possibly did not differ materially from the calculated composition given on page 472. This course of differentiation produced primarily and most abundantly the granites, quartz-syenites, and diorites, with their corresponding aschistic dikes as *Nachschube.* A secondary local differentiation of the more basic differentiates of this process gave rise to the foyaites and essexites, while the rocks of the paisanite-tinguaite series are probably diaschistic dike forms of these. At a much later period, after erosion had removed much of the covering of the granolites, the rhyolites were erupted, from some unknown vents. Lastly, here, as so often elsewhere, the diabases were injected into the much cracked complex.

Comparison with other regions.— So much space has been devoted to the previous discussion that a few words must suffice for this topic. From the references to the Christiania region throughout the paper and comparison of the analyses, the general correspondence between the two is evident. There are differences in details, such as the more acid and somewhat less soda-rich character of the Essex county rocks, abundance of diorites here and of laurvikites and laurdalites in Norway, etc. But it may be said that the general course of differentiation was essentially much the same in both, a fact which supports the theory that the variations of rocks are largely subject to physico-chemical laws, and are not fortuitous and due to the composition of the surrounding rocks and other external circumstances, as Johnston-Lavis and Becker would have us believe.

A comparison could also be instituted with the other igneous rocks of the New England region, going to show that great similarities exist. But our knowledge of most of the other igneous regions of New England and Canada is so scanty that the time does not seem ripe for this. It will be sufficient to note that some of the rocks of Essex county show great analogies with, for instance, those of Litchfield, Maine, and Red Hill and Mt. Ascutney, New Hampshire. Farther west, in the Adirondacks and near Montreal, the character of the magma seems to be different, as has been pointed out recently by Cushing,[1] though there are many resemblances.

HENRY S. WASHINGTON.

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[1] H. P. CUSHING: Bull, Geol. Soc. Amer., Vol. X, p. 191, 1899.

TABLE I.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
SiO_2	77.61	77.14	76.49	73.93	71.40	70.64	68.88	68.36	67.35	66.60	64.28	63.71
TiO_2	0.25	0.29	trace	0.18	.....	0.90	0.19	trace	0.60	0.76	0.50	trace
ZrO_2	.....	.....	.....	.....	.....	.....	.. ..	.....	.....	.....	.....	.....
Al_2O_3	11.94	12.24	11.89	12.29	14.76	15.34	14.77	16.58	15.05	15.05	15.97	18.30
Fe_2O_3	0.55	0.29	1.16	2.91	1.68	1.83	0.64	0.90	1.23	1.07	2.91	2.08
FeO	0.87	1.04	1.56	1.55	0.72	1.10	4.64	3.24	4.76	4.42	3.18	2.52
MnO	trace	trace	trace	trace	trace	trace	trace	trace	0.05	trace	trace	trace
MgO	trace	0.06	trace	0.04	0.55	0.52	0.37	0.45	0.03	0.36	0.03	0.09
CaO	0.31	0.35	0.14	0.31	0.10	1.24	1.74	1.85	0.55	2.21	0.85	1.18
BaO	.....	.....	.....	none	.....	.....	.....	.....	.....	none	none	.....
Na_2O	3.80	4.64	4.03	4.66	4.79	5.23	3.83	3.97	4.42	4.03	7.28	6.39
K_2O	4.98	4.47	5.00	4.63	5.16	3.55	4.97	5.27	6.08	5.42	5.07	6.21
H_2O (110°)	trace	trace	0.12	.....	.....	0.14	0.06	0.18	0.16	.....	.....	0.09
H_2O (ignit)	0.23	0.14	0.38	0.41	1.46	0.38	0.24	0.17	0.17	0.41	0.20	0.17
P_2O_5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.08	.....
	100.54	100.66	100.77	100.91	100.62	100.87	100.33	100.97	100.45	100.33	100.33	100.74
Sp. Gr.	2.618		2.650	2.642		2.632	2.696		2.690	2.612	2.703	2.686
at	18°C.		13°C.	22°C.		12.5°C.	12°C.		17°C.	17°C.	22°C.	12°C.

TABLE I — *Continued.*

	XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV
SiO_2	63.09	61.05	60.05	59.31	58.77	56.75	51.82	47.12	46.99	46.59	45.32	43.73
TiO_2	0.45	0.34	0.11	0.32	0.31	0.30	2.15	3.27	2.92	1.41	1.94	4.23
ZrO_2	0.06	.....	.....	.....	0.11	.....	.....	.....	.....	.....	.....	... .
Al_2O_3	18.50	18.81	19.97	22.50	22.64	20.69	17.06	14.43	17.94	17.55	18.99	20.17
Fe_2O_3	2.90	2.02	4.32	1.93	1.54	3.52	1.97	3.33	2.56	1.68	3.78	4.32
FeO	1.36	3.06	1.04	1.40	1.04	0.59	8.60	11.71	7.56	10.46	9.78	6.93
MnO	trace	trace	0.79	trace	trace	trace	trace	.....	.....	.....	.....	.....
MgO	0.16	0.42	0.23	0.17	0.19	0.11	4.87	6.05	3.22	7.76	4.68	3.91
CaO	1.00	1.30	0.91	0.46	0.74	0.37	8.59	9.63	7.85	10.64	9.19	10.99
BaO	.....	none	.....	.....	none	none	.....	.....	none	.....	.....	.....
Na_2O	7.25	6.56	7.69	7.98	9.62	11.45	3.44	2.58	6.35	3.31	3.78	2.42
K_2O	5.23	6.02	3.24	4.08	4.89	2.90	1.77	1.11	2.62	0.72	2.12	1.45
H_2O (110°)	0.21	.....	0.15	0.15	0.07	0.04	0.11	0.28	.....	0.10	0.09	0.08
H_2O(ignit)	0.62	0.78	1.26	1.12	0.90	3.18	0.20	0.34	0.65	0.07	0.31	1.02
P_2O_5	.....	.....	Cl=0.28	.....	.....	Cl=0.28	.....	.....	0.94	.....	.....	0.15
	100.83	100.36	100.04	99.42	100.82	100.18	100.58	99.85	99.60	100.29	99.98	99.40
Sp. Gr.		2.655	2.708	2.599	2.596	2.474		3.072	2.919	3.047	2.975	3.058
at		12°C.	....	12°C.	11°C.	22°C.		12°C.	12°C.	11°C.	11°C.	11°C.

I. Granite. Rockport.
II. Aplite (mean). Bass Rocks.
III. Paisanite. Magnolia.
IV. Granite. Quincy. (Blue Hills.)
V. Keratophyr. Marblehead Neck.
VI. Rhyolite. Marblehead Neck.
VII. Quartz-syenite-porphyry. Squam Light.
VIII. Nordmarkite. Wolf Hill.
IX. Enclosure in Granite. Rockport.
X. Akerite. Gloucester.
XI. Sölvsbergite. Andrew's Point.
XII. Pulaskite. Salem Neck.

XIII. Pulaskite. Salem Neck.
XIV. Sölvsbergite. Coney Island.
XV. Tinguaite. Gale's Point. (Eakle.)
XVI. Foyaite. Great Haste Island.
XVII. Foyaite. Salem Neck.
XVIII. Tinguaite. Pickard's Point.
XIX. Diorite. Marblehead.
XX. Diabase. Rockport.
XXI. Essexite. Salem Neck.
XXII. "Camptonite." Salem Neck.
XXIII. Hornblende Gabbro. Salem Neck.
XXIV. Gabbro. Nahant.

TABLE II.

	Ia	IIa	IIIa	IVa	Va	VIa	VIIa	VIIIa	IXa	Xa	XIa	XIIa
SiO_2	1.294	1.286	1.275	1.232	1.190	1.177	1.148	1.139	1.123	1.110	1.071	1.062
Al_1O_3	.117	.120	.117	.120	.145	.150	.145	.163	.148	.148	.156	.179
Fe_2O_3	.003	.001	.007	.018	.011	.011	.004	.006	.008	.007	.018	.013
FeO	.012	.014	.022	.022	.010	.014	.064	.045	.066	.061	.044	.035
MgO	....	.002	....	.001	.014	.013	.009	.011	.001	.009	.001	.002
CaO	.005	.006	.002	.006	.002	.022	.031	.033	.010	.039	.015	.021
Na_2O	.061	.075	.065	.075	.077	.084	.062	.064	.071	.065	.117	.103
K_2O	.053	.048	.053	.049	.055	.038	.053	.056	.065	.058	.054	.066
$\frac{Na_2O}{K_2O}$	1.15	1.56	1.23	1.53	1.40	2.21	1.17	1.14	1.09	1.12	2.17	1.71
$\frac{FeO}{Fe_2O_3}$	4.00	14.00	3.14	1.22	0.91	1.28	16.00	7.50	8.25	8.71	2.44	2.69
$\frac{Na_2O+K_2O}{SiO_2}$	.088	.096	.092	.101	.111	.104	.100	.105	.121	.111	.156	.159
$\frac{Na_2O}{SiO_2}$	.047	.059	.051	.061	.065	.071	.054	.057	.063	.059	.110	.097

TABLE II.—*Continued.*

	XIIIa	XIVa	XVa	XVIa	XVIIa	XVIIIa	XIXa	XXa	XXIa	XXIIa	XXIIIa	XXIVa
SiO_2	1.052	1.018	1.001	0.989	0.980	0.946	0.864	0.785	0.783	0.777	0.766	0.729
Al_2O_3	.181	.183	.196	.221	.222	.203	.167	.142	.176	.172	.186	.198
Fe_2O_3	.018	.013	.027	.012	.010	.022	.012	.021	.016	.011	.023	.027
FeO	.014	.043	.014	.019	.014	.008	.120	.163	.105	.145	.136	.097
MgO	.004	.011	.005	.004	.005	.003	.122	.151	.080	.194	.117	.098
CaO	.018	.023	.016	.008	.013	.007	.153	.172	.140	.190	.164	.196
Na_2O	.117	.158	.123	.129	.155	.185	.056	.042	.102	.053	.061	.039
K_2O	.056	.064	.034	.043	.052	.031	.019	.012	.029	.008	.023	.015
$\frac{Na_2O}{K_2O}$	2.09	2.47	3.62	3.00	2.98	5.97	2.95	3.50	3.64	6.63	2.65	2.60
$\frac{FeO}{Fe_2O_3}$	0.78	3.31	0.52	1.58	1.40	0.37	10.00	7.74	6.57	13.19	5.67	3.96
$\frac{Na_2O+K_2O}{SiO_2}$	.164	.218	.157	.174	.211	.228	.086	.069	.166	.078	.112	.074
$\frac{Na_2O}{SiO_2}$	.111	.155	.123	.130	.157	.195	.065	.053	.130	.068	.080	.053